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ABSTRACT

This booklet is one in the "World of the Atome Series" for junior high school students and their teachers. It describes the fascinating story of the search for the key to the structure of matter. These topics are reviewed: the chemical atom of the 19th century, the planetary atom, the wave atom, inside the elementary particles, and the mystery of matter. Numerous photographs are included throughout the text. (PR)

The Mystery of Matter

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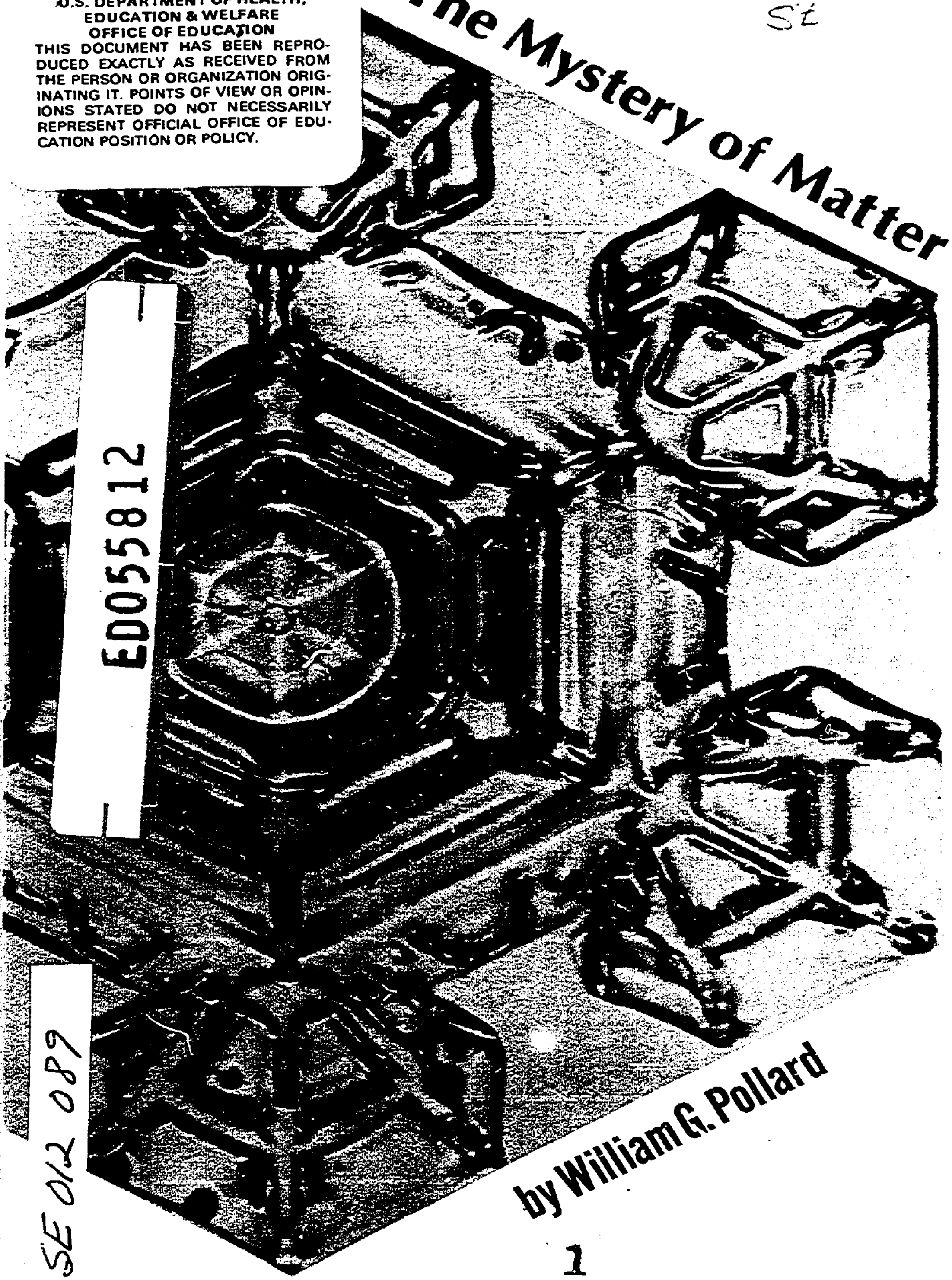


by William G. Pollard

. . . on a rainy morning in the West. . . . I had come up a long gulch looking for fossils, and there, just at eye level, lurked a huge yellow-and-black orb spider, whose web was moored to the tall spears of buffalo grass at the edge of the arroyo. It was her universe, and her senses did not extend beyond the lines and spokes of the great wheel she inhabited. Her extended claws could feel every vibration throughout that delicate structure. She knew the tug of wind, the fall of a raindrop, the flutter of a trapped moth's wing. Down one spoke of the web ran a stout ribbon of gossamer on which she could hurry out to investigate her prey.

Curious, I took a pencil from my pocket and touched a strand of the web. Immediately there was a response. The web, plucked by its menacing occupant, began to vibrate until it was a blur. Anything that had brushed claw or wing against that amazing snare would be thoroughly entrapped. As the vibrations slowed, I could see the owner fingering her guidelines for signs of struggle. A pencil point was an intrusion into this universe for which no precedent existed. Spider was circumscribed by spider ideas; its universe was spider universe. All outside was irrational, extraneous, at best, raw material for spider. As I proceeded on my way along the gully, like a vast impossible shadow, I realized that in the world of spider I did not exist.

. . . Man, too, lies at the heart of a web, a web extending through the starry reaches of sidereal space, as well as backward into the dark realm of prehistory. His great eye upon Mount Palomar looks into a distance of millions of light-years, his radio ear hears the whisper of even more remote galaxies, he peers through the electron microscope upon the minute particles of his own being. It is a web no creature of earth has ever spun before. Like the orb spider, man lies at the heart of it, listening. Knowledge has given him the memory of earth's history beyond the time of his emergence. Like the spider's claw, a part of him touches a world he will never enter in the flesh. Even now, one can see him reaching forward into time with new machines, computing, analyzing, until elements of the shadowy future will also compose part of the invisible web he fingers.

. . . What is it we are a part of that we do not see, as the spider was not gifted to discern my face, or my little probe into her world?

Loren Eiseley

THE WORLD OF THE ATOM SERIES

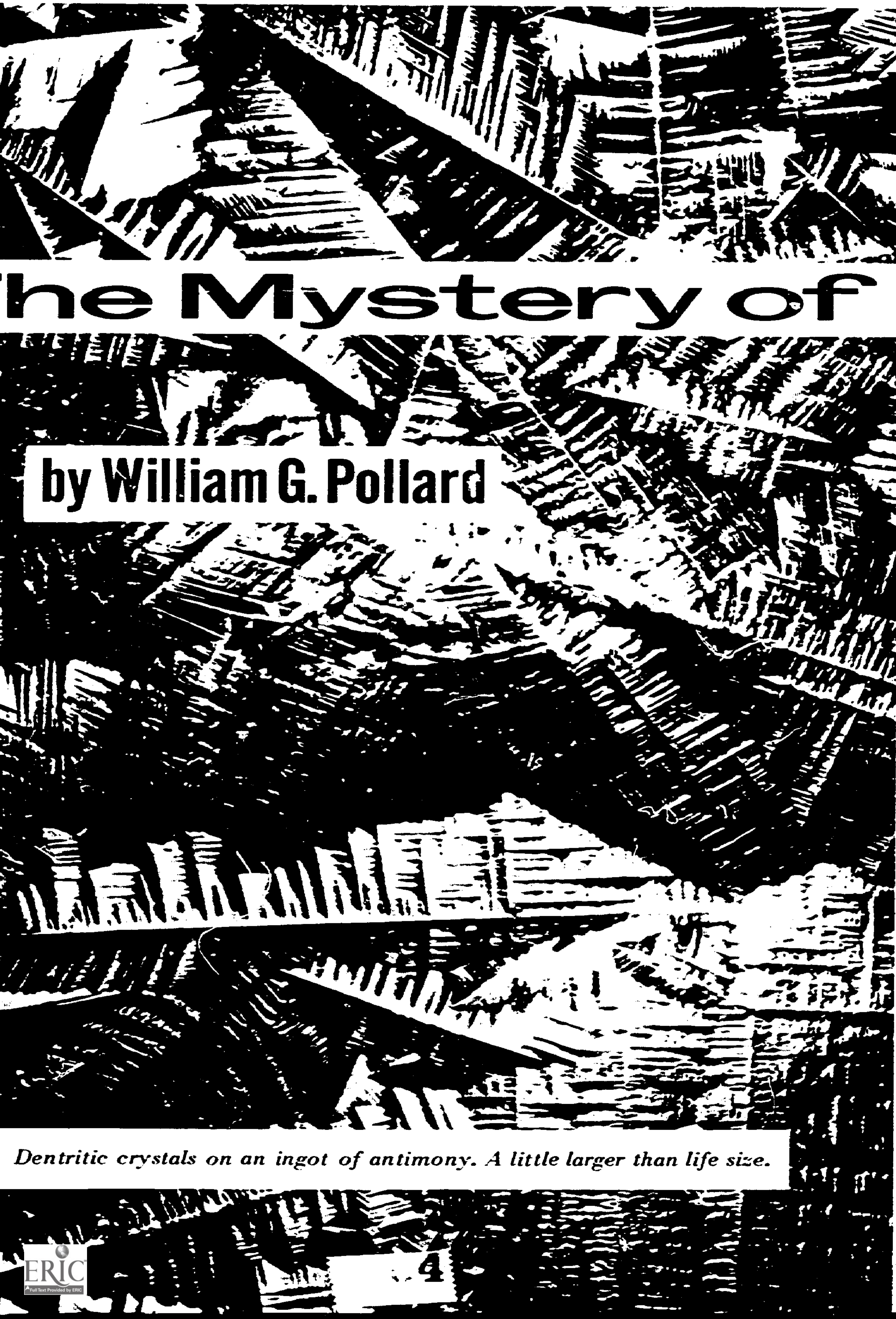
Foreword

This booklet is one in a series for junior high school science students and their teachers. It describes the fascinating story of the search for the key to the structure of matter.

I hope you enjoy reading this booklet.

Edward J. Brunenkant

Edward J. Brunenkant, Director
Division of Technical Information



The Mystery of

by William G. Pollard

Dentritic crystals on an ingot of antimony. A little larger than life size.

Matter

CONTENTS

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1970

I would not like to underestimate the value of the world view which is the result of scientific effort. We have been led to imagine all sorts of things infinitely more marvelous than the imaginings of poets and dreamers of the past. It shows that the imagination of nature is far, far greater than the imagination of man. For instance, how much more remarkable it is for us all to be stuck—half of us upside down—by a mysterious attraction, to a spinning ball that has been swinging in space for billions of years, than to be carried on the back of an elephant supported on a tortoise swimming in a bottomless sea.

Richard Feynman

Introduction

Matter presents itself to our immediate experience in a great diversity of forms. For primitive man there were the major divisions between sea and earth and sky. Each of these domains contained its own diversity. The dry land had sand and soil, rocks and minerals, trees and grass. In the sky were air and rain, wind and storm, and above all the mysterious sun, moon, and stars. The sea was a vast immensity of water populated by creatures both small and great that served for the nourishment of man's body as well as for the terror of his soul.

Yet all of this in one way or another was matter. Is there some secret hidden in the heart of matter that gives unity to this bewildering diversity? Can the imagination and the reason of man probe beneath the surface of his immediate experience and unmask this secret? It is a fascinating question and from time to time in the long history of speculative thought it has been a dominant force.

Early Theories of Matter

At the beginnings of Greek philosophy one possible clue was seized upon. Perhaps all could be understood in terms of four basic elements: air, fire, water, and earth. As a beginning this had much to commend it. After all, fire and earth were the ingredients from which iron, copper, and bronze were derived. Wind, water, and fire are commingled in storms. The combination of water and earth leads to fertility, and man, as was widely believed, was made of the dust of the earth but became a living being only when the breath of life was breathed into him. Here was certainly a first step in the long quest to unlock the inner secret of matter.

Later in a more sophisticated vein a genuine atomic theory of matter emerged with Leucippus and Democritus. One of the notions that led them to this theory was the thought of dividing any piece of matter into smaller and smaller halves. Ultimately, they agreed, one must come to a point where further division is impossible. Such a smallest or minimum piece of matter was an "atom".

Epicurus

Later the philosopher Epicurus elaborated this line of thinking into a well-developed atomic theory of matter. As the common designation "epicurean", reveals, he is best known today for his hedonism. This is chiefly because the modern scientific atomic theory is so recent. Prior to it, the knowledge against which to evaluate his substantial achievement did not exist.

Lucretius and the *De Rerum Natura*

At the peak of the classical period, Titus Lucretius Carus, a contemporary of Julius Caesar and of Cicero, wrote the most complete account of the atomic theory of matter that Gracco—Roman philosophy produced. He was an ardent admirer of Epicurus. His sole work is a long epic poem on the nature of things entitled *De Rerum Natura.*

It is a unique contribution to the literature of mankind in that, unlike other epics of similar length, it is not devoted to great human exploits and deeds, but rather attempts to develop a complete and comprehensive scientific description of the whole universe. It covers the infinity of space, cosmology, the structure of matter; other worlds with their own earth, sun, and moon; the evolution of life and genetics; the origin of man and his development from primitive wild states to civilized societies. Nothing quite like it has ever been attempted before or since.

Lucretius repeats the earlier arguments against the indefinite divisibility of matter as the most basic argument for atoms, but he uses a number of others that are remarkably perceptive. One of these is based on transformations of matter. Veins, blood, bones, and sinews are formed out of the food we eat. Flowers, shrubs, and trees are formed from the earth and water in which they grow. Wood is converted through burning into flame, smoke, and ashes.

In all these cases the atoms are eternal and unchangeable. Different combinations with different motions and with varying amounts of void between them account for these transformations from one kind of substance into another.

Another argument comes very close to the Brownian motion as evidence of the atomic character of matter. Here Lucretius notes that when a ray of sunlight passes through the dark hall of a house, one sees in it many specks or mites in incessant motion, tumbling and jerking as from invisible blows. He concludes that the invisible atoms are in a similar incessant motion and make collisions with next larger objects, with the result that the primeval motions ascend stage by stage to a point where we can observe such motions directly.

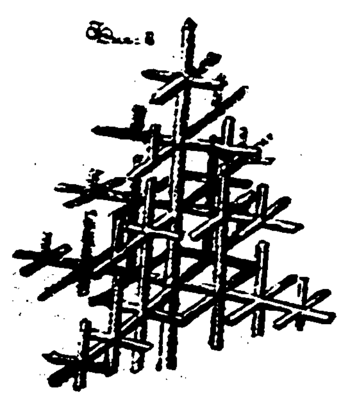
Just as the letters of the alphabet can be used in different combinations to produce a great variety of words and these in turn can express a vast range of ideas, so all things in existence come into being through particular combinations of atoms and then disintegrate into the same atoms again. The atoms themselves never change, but their associations, motions, and proportions are in a continual state of flux. As he puts it at one point in his poem:*

"... for these
Same germs do put together sky, sea, lands,
Rivers, and sun, grains, trees, and breathing things,
But yet commixed they are in divers modes
With divers things, forever as they move."

*Lucretius, *Of the Nature of Things*, translated by William Ellery Leonard, Everyman's Library edition, Book I, p. 31.

From our vantage point 2000 years later, Lucretius shows many amazing flashes of insight. Yet in spite of these striking parallels to a modern scientific view of the nature of things, his entire poem is pure speculation based on general experience, and untouched by the discipline of the slow and painstaking verification of ideas that has gradually built our view. Indeed, we gain an impression of his exceptional insight largely by selecting instances of his thought that *agree* with our view of things.

There are, however, numerous instances in his poem of notions that are ludicrous from a modern vantage point. For example, he suggests that honey or syrup is made of smooth, round atoms, while bitter or acid foods are made of sharp-edged or barbed atoms. He uses the same idea in explaining the difference between freshwater and seawater. The hardness and strength of rocks and iron are attributed to a tortuous and irregular configuration of their atoms that causes them to intertangle and form a rigid structure. The mind and soul he considers formed from extremely small atoms in a very dilute state.

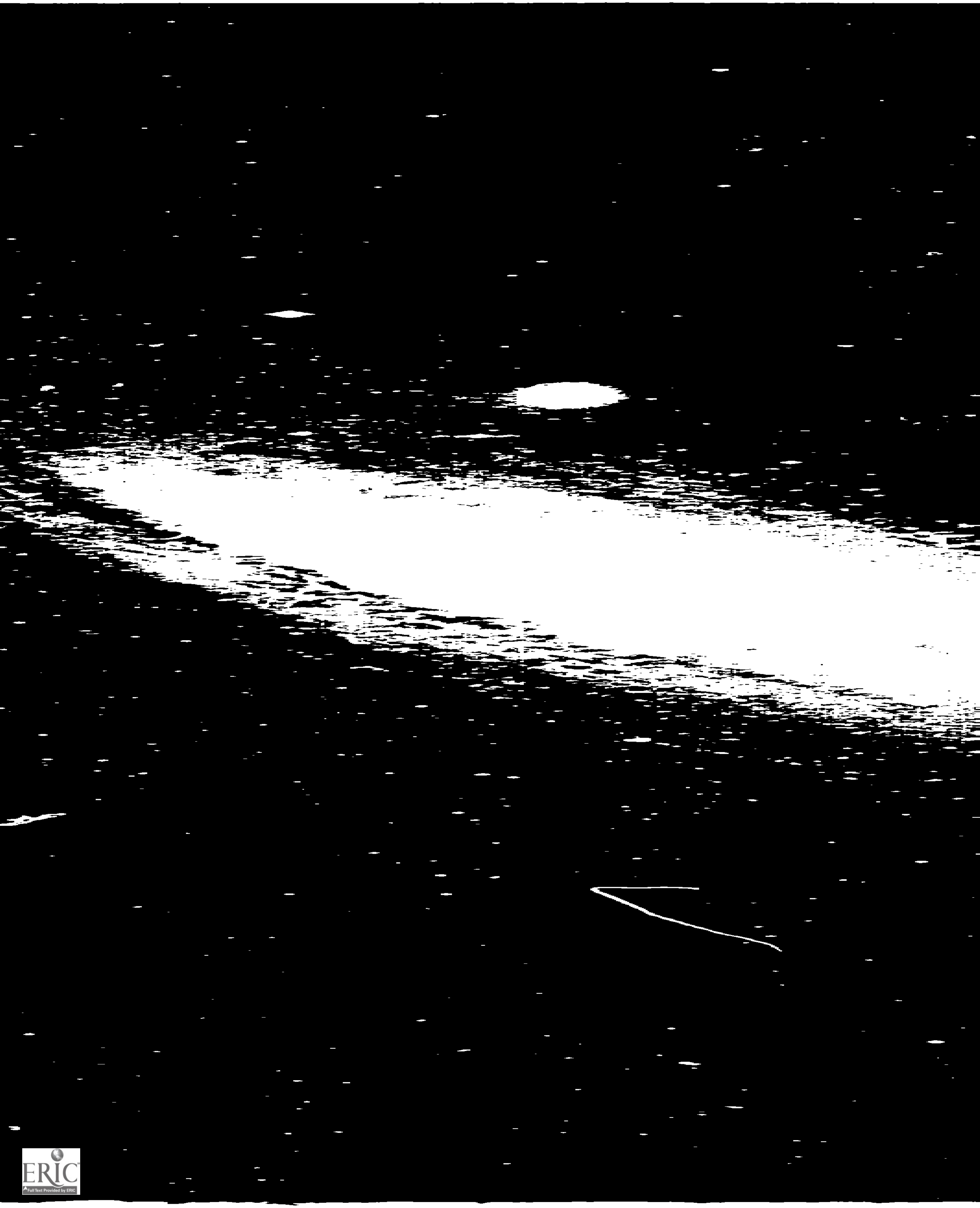


An iron crystal

Lucretius had little effect on his contemporaries, although Cicero admired his poem and was probably responsible for its preservation. But he was not widely read and had no discernible influence on subsequent thought. Indeed, the whole of Greek atomism had surprisingly little influence and seemed to be of little interest in the classical period.

Only in the Renaissance was Lucretius rediscovered and in the 15th and 16th centuries numerous editions of his poem were

produced. It was then that the idea of a systematic and unified view of nature, which was Lucretius' passionate vision, began to attract and excite the minds of men, both those who admired Lucretius and those who opposed him. He formed the link between the classical quest for the secret of matter and the new scientific quest that began in the 17th century. We now turn to this quest and the strange depths of reality to which it has led us.



. . . a physics book, unlike a novel, not only has no happy ending, but has no real ending at all.

Jeremy Bernstein

The Chemical Atom of the 19th Century

The idea of atoms as the elementary constituent of matter blossomed in the Renaissance from the thin line it had followed through the centuries from ancient Greece. At the dawn of modern science in the beginning of the 17th century, it was popularized by the philosopher Pierre Gassendi and accepted by Galileo Galilei, Isaac Newton, and Robert Boyle. But with all of them it remained a rather vague general idea, unattached to any specific facts or processes.

John Dalton and the Atomic Theory

It was left to a Cumberland, England, handloom weaver named John Dalton to begin the process by which atoms became concrete and identifiable. This he did, in the first decade of the 19th century, through the idea that atoms come in classes with all atoms in each class being identical, and each class constituting a chemical element. Although Lucretius had thought of atoms running in classes, his classes were based on shape and geometrical form. The idea of chemical elements was distinctly new and of course turned out to be immensely fruitful.

John Dalton

As with all great ideas, this one had its history. In 1783 Henry Cavendish sparked hydrogen and oxygen in a closed volume and noticed that only water was produced and that the initial and final volumes were in the simple ratio of three to two. This was the first instance of what gradually came to be recognized as a general fact—the "law of simple multiple proportions".

In time each chemical element could be assigned an "atomic weight". Careful experiments by Dalton and others showed that whenever two or more elements combined chemically to make a compound, the relative amounts had to fit a definite proportion if none of the elements was left over after the reaction was complete.

Thus emerged the picture of all matter made up of a relatively small number of chemical elements, each of which consisted of small, indivisible, and identical atoms. These elementary atoms combined in definite proportions to form molecules, which were the smallest units of compounds formed from two or more elements.

Dmitri Mendeleev and the Periodic Table of Elements

Throughout the 19th century this idea was elaborated into a complete theory of the nature of matter far grander and more unified in scope, and much more concrete in application than Lucretius ever dreamed of. Dmitri Mendeleev, a Russian chemist, perfected the periodic arrangement of elements that brought out the similarities of groups, such as chlorine, bromine, and iodine, and showed gaps indicating undiscovered elements. This

Dmitri Mendeleev and his Periodic Table of the Elements.

ОПЫТЪ СИСТЕМЫ ЭЛЕМЕНТОВЪ.

ОСНОВАННОЙ НА ИХЪ АТОМНОМЪ ВѢСѢ И ХИМИЧЕСКОМЪ СХОДСТВѢ.

			Ti = 50	Zr = 90	? = 180.
			V = 51	Nb = 94	Ta = 182.
			Cr = 52	Mo = 96	W = 186.
			Mn = 55	Rh = 104,4	Pt = 197,4.
			Fe = 56	Rn = 104,4	Ir = 198.
			Ni = Co = 59	Pl = 106,6	Os = 199.
H = 1			Cu = 63,4	Ag = 108	Hg = 200.
	Be = 9,4	Mg = 24	Zn = 65,2	Cd = 112	
	B = 11	Al = 27,4	? = 68	Ur = 116	Au = 197?
	C = 12	Si = 28	? = 70	Sn = 118	
	N = 14	P = 31	As = 75	Sb = 122	Bi = 210?
	O = 16	S = 32	Se = 79,4	Te = 128?	
	F = 19	Cl = 35,5	Br = 80	I = 127	
Li = 7	Na = 23	K = 39	Rb = 85,4	Cs = 133	Tl = 204.
		Ca = 40	Sr = 87,6	Ba = 137	Pb = 207.
		? = 45	Ce = 92		
		?Er = 56	La = 94		
		?Yt = 60	Di = 95		
		?In = 75,6	Th = 118?		

Д. Менделѣевъ

arrangement also gave order to the idea of valence, which pointed the way to systematizing the kinds of compounds that any element could form.

The Chemical Nature of Matter

In the last half of the century a great flowering of organic chemistry occurred, and the structures of a great variety of biologically important compounds were worked out. The vast variety of nature, both inanimate and animate, was surely and steadily yielding to the discovery of what seemed to be her innermost secret.

That secret was the underlying simplicity of some 90 elements whose atoms formed the irreducible and eternal constituents of all matter. With these atoms the almost infinite variety of molecules could, in principle, and increasingly in fact, be built in precise ways, which were described by chemical formulae that revealed their exact structures. Not only could the 19th century confidently support Lucretius that "sky, sea, lands, rivers, and sun, grains, trees, and breathing things" are put together out of these 90 elements, but it could go further and show precisely which atoms were involved in each case and how they were combined.

Atomic and Molecular Motion

Striking as this achievement was, the atomic theory of the 19th century went considerably beyond it by explaining a variety of other phenomena with its atoms. The first step was the recognition that heat is mechanical energy at the atomic level. This was

verified quantitatively in a series of beautiful experiments during the first half of the century. In a gas, like air, the molecules are in continual motion. The temperature of the gas was a measure of the average energy of any given mode of motion (rotation, vibration, etc.) of which the molecules are capable.

When the gas is heated, the total amount of energy put into it distributes itself over all modes of motion of all its molecules. From a knowledge of these modes of motion and the number of molecules in the gas, the temperature rise for a given input of energy can be computed.

Moreover, the pressure exerted by the gas on the walls of its container is the result of the continual bombardment of molecules striking the walls and reflecting from them. In solids, the atoms and molecules can only vibrate about fixed positions. When a solid is heated, the energy goes into increased vibration of the atoms, and the temperature is increased in proportion as the average energy of each mode of vibration is increased.

This line of development led to the formulation of thermodynamics as a general description of the behavior of heat in all physical or chemical systems. By the end of the century the properties of gases were well described in the kinetic theory. James Clerk Maxwell and Ludwig Boltzmann had developed statistical mechanics so that it gave a detailed picture of the distribution of velocities throughout the molecules of a gas, the manner in which atoms or molecules share energy among themselves, and the different ways in which they are free to move. The

solid, liquid, and gaseous phases of matter were well understood in a general way.

This atomic theory of the 19th century was an immense achievement of human understanding. When the century began, the idea of atoms had scarcely changed since Lucretius and his Greek atomist predecessors. As it came to a close, most of the elementary atoms of nature had been identified and their relative weights determined.

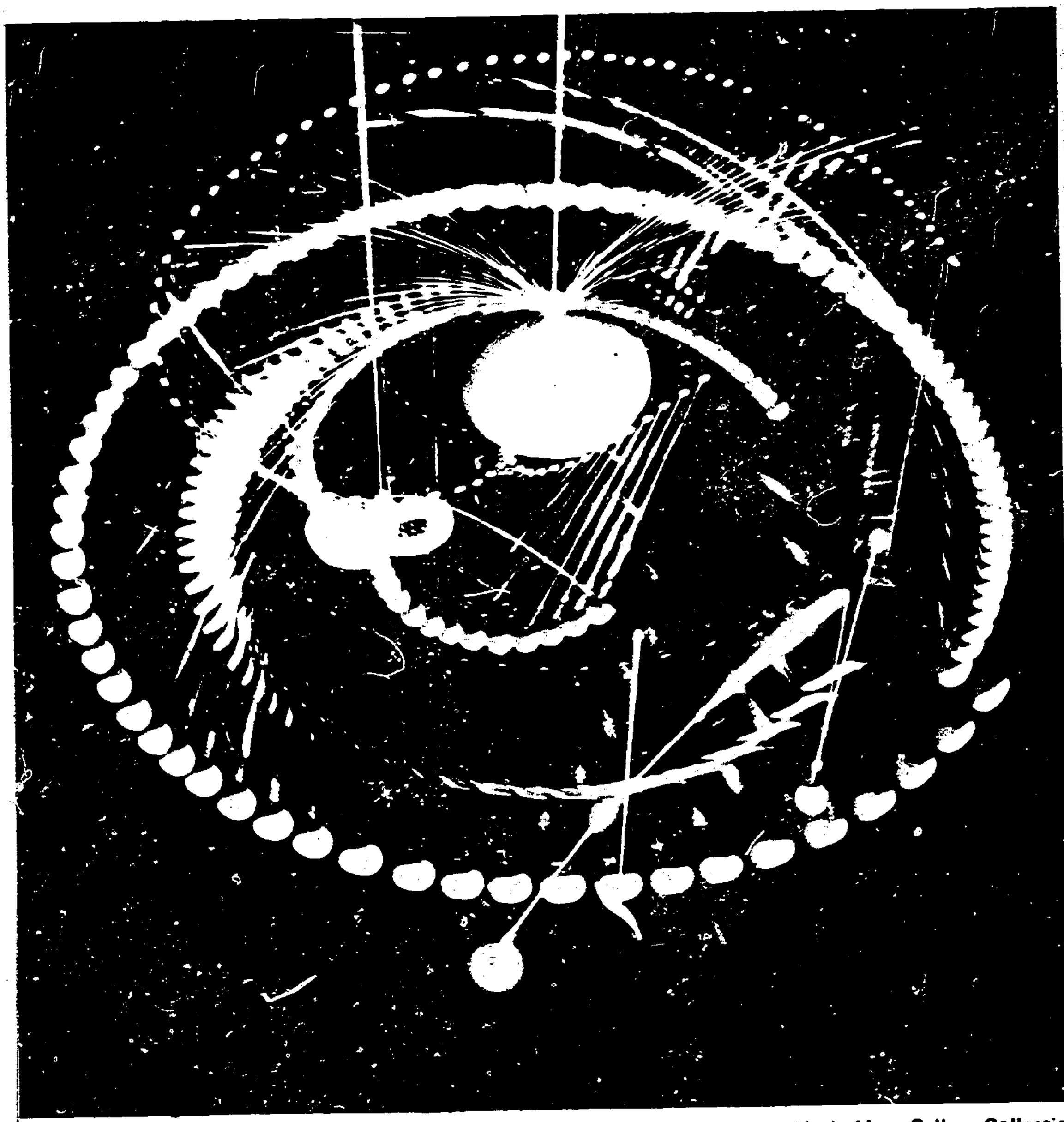
A tremendous number of substances—metals, minerals, salts, fluids, gases, and numerous organic materials found in living systems—had been precisely defined as specific combinations of these elements. The motions executed by these atoms or molecules had also been meticulously defined. The several states in which matter is found were rather well understood in terms of forces between molecules and the motions of the molecules.

Much insight had been achieved into the mechanical and thermal properties of different substances in their solid or gaseous phases. *The nature of matter was understood in a beautifully structured system of great internal consistency and elegance, such as even Lucretius in his most fanciful moments could never have imagined possible.* Not only was this synthesis conceptually elegant, but it further authenticated itself by leading to many practical applications in synthetic chemicals, steam and internal combustion engines, and the like.

In the first flush of enthusiasm over such an achievement in a bare hundred years of human history, the universal tendency was to think of nature as more or less transparent.

The secret of matter seemed to lie not far below the surface. The achievement was the result of many investigators working in different fields on a variety of seemingly unrelated problems. Yet the results of their labors often converged to bring out some new and unexpected facet of the total picture.

It was as though nature were like a vast maze with many openings on its perimeter through which scientists entered in search of her secrets. Yet as successive hurdles to understanding were overcome, the separate channels of the maze seemed to be leading to the one great secret at the center. Wherever one started at the surface, one would ultimately wind inward to this central principle at the heart of reality.



The Museum of Modern Art, New York, Mary Callery Collectio

From the oscillating universe, beating like a gigantic heart, to the puzzling existence of antimatter, order, in a human sense, is at least partially an illusion. Ours, in reality, is the order of a time, and of an insignificant fraction of the cosmos, seen by the limited senses of a finite creature.

Loren Eiseley

The Planetary Atom

The quest for the central secret of the nature of matter in the 20th century has had many surprises. Not the least of these is the realization that there seem to be limitless depths in nature. The feeling at the end of the 19th century—that the explanation of nature lay just below the surface and that its major outlines had already been mapped out—has proved to be quite deceptive.

We have been plunged successively into three deeper levels below that reached by the beginning of the century. Each of these levels is something like a whole world undergirding and explaining the one above it. Yet at each stage of exploration of one level the very existence of the level below was unrecognized until most of the exploration in the preceding level had been carried out.

Throughout this century the quest for the secret of matter has been an exciting one filled with amazement and many surprises along the way. As a result we no longer think of nature as shallow and of matter as basically simple and rather obvious when its secret is revealed. *On the contrary nature seems to have apparently inexhaustible depths and matter to have inner symmetries and structures of great beauty, which are neither simple nor obvious but rather intricate and strange.*

The 19th century atoms were hard elastic spheres with no inner structure of their own and possessing mass as the sole basic property of the matter of which they were constituted. Yet parallel with the development of the atomic synthesis, which the chemists and thermodynamicists were achieving, a number of physicists had been investigating an apparently unrelated phenomenon—electricity. When dissolved in water a number of atoms became electrically charged. Such charged atoms were called "ions".

Michael Faraday

Michael Faraday and Electrolysis

Michael Faraday had studied the process of electrolysis (familiar in electroplating and in storage batteries) of such ions in solution. The most important result of his investigations was that the amount of electricity on ions of all kinds was always a simple integral multiple of a fundamental amount, either positive or negative; this unit is called the faraday.

This was the minimum amount of electricity carried by a sufficient number of ions to make a mass in grams numerically equal to the atomic weight of their atoms. How many atoms were required to do this was unknown then, so that the amount of mass and electric charge on each ion could not be determined.

Wilhelm Roentgen

Electricity and Magnetism

In other studies it was also found that metals and some other substances had the property of conducting electricity. A current of electric charge could be made to flow through them continuously under certain conditions. Different metals were characterized by offering different amounts of resistance to the flow of such a current.

Yet for most of the century the relationship between these electrical properties of metals and of ions in solution and the developing atomic theory was not suspected. Electricity and magnetism were simply interesting auxiliary phenomena to be studied in their own right, but not apparently significant in the quest for the secret of matter and the atoms of which it is made.

J. J. Thomson

The Electron

Then at the very end of the century, Wilhelm Roentgen discovered the mysterious X rays and Joseph J. Thomson discovered the electron. Suddenly with these discoveries electricity came to play a fundamental role in atoms. The new electrons were over a thousand times less massive than even the lightest

atom and yet they were clearly a constituent of matter. In the first quarter of this century a series of brilliant experiments led to the development of the solar system model of atoms, which is still the popular picture in the nonscientific world.

Other Atomic Particles

Far from being pictured as the simple elementary spheres of the last century, atoms were now seen to be complex structures of more elementary particles. These particles are the neutron, proton, and electron. Each atom consists of a small central body called the nucleus, which is made up of neutrons and protons and contains almost all the atom's mass. A number of negatively charged electrons equal to the number of positively charged protons move around the central massive nucleus in planet-like orbits.

This picture of the nature of matter dramatically reduced the number of elements from the 90 or so atoms of the chemists to just three basic elementary particles. Protons and neutrons could be combined in a variety of ways so as to obtain a rich assortment of nuclei.

In these combinations the number of protons determined which of the chemical elements that nucleus would form when it collected its full complement of electrons. This is because the chemical properties of the atom, such as the kinds of molecular compounds it would form, its position in the periodic table, etc., depend only on the

electrons circulating around the nucleus, and not on the properties of the central nucleus itself.

By analogy we might suppose that the differences between our solar system and other similar ones would depend on the number of planets in them, their size and mass, and the kinds of orbits they execute around their central sun. The stars at their center would be very much like our sun. In the case of atoms, those with one electron are hydrogen, those with six are carbon, those with twenty-six are iron, and those with ninety-two are uranium.

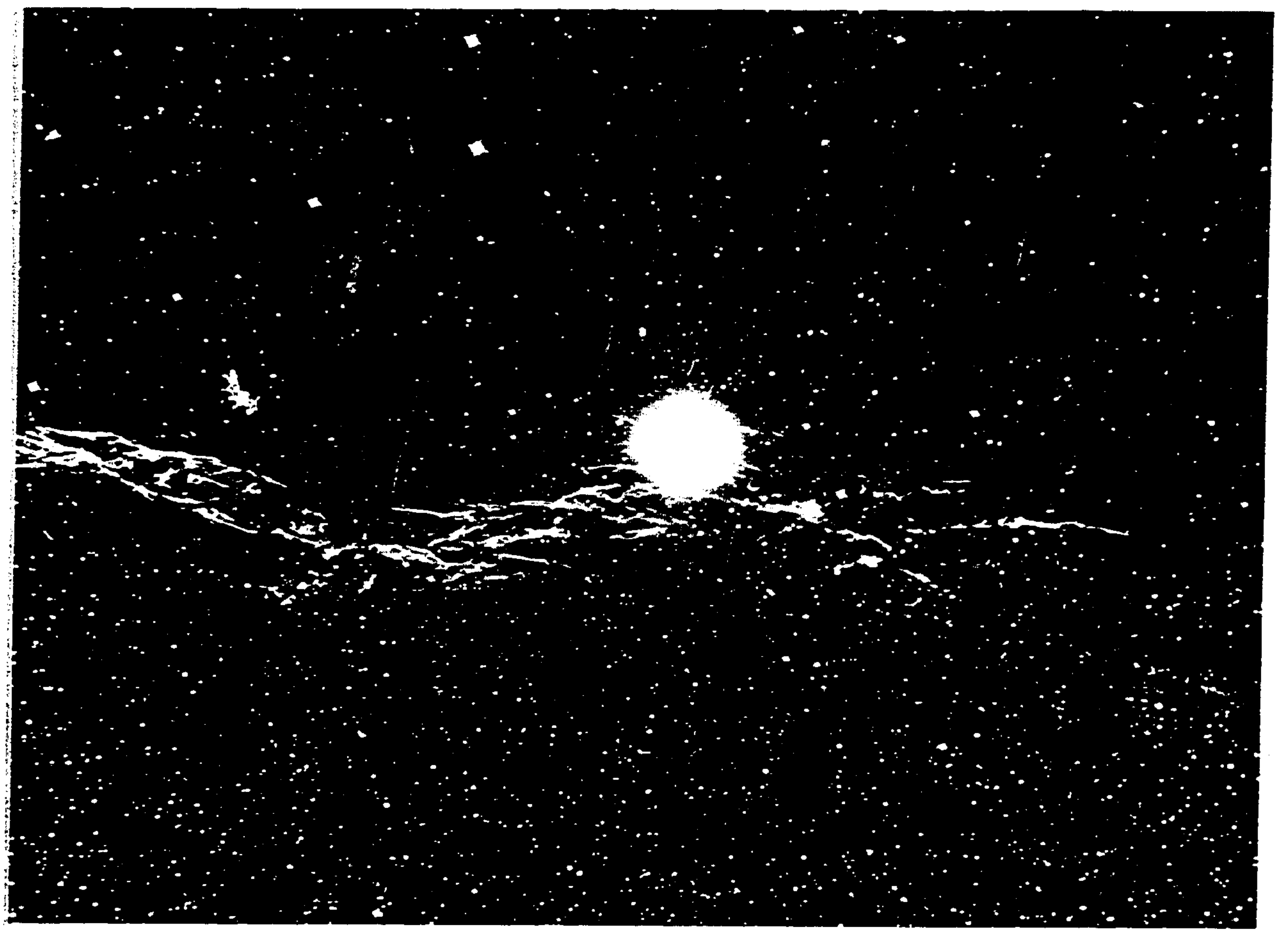
Nuclei with the same number of protons but different numbers of neutrons are called "isotopes" of the same chemical elements. Thus the simplest element, hydrogen, with only one proton and one electron has three isotopes. The lightest and most common has no neutrons at all and its nucleus consists of a single isolated proton. Heavy hydrogen or deuterium has a nucleus with one proton and one neutron, and a radioactive form of hydrogen called tritium has one proton and two neutrons in its nucleus.

Electricity and the Structure of Matter

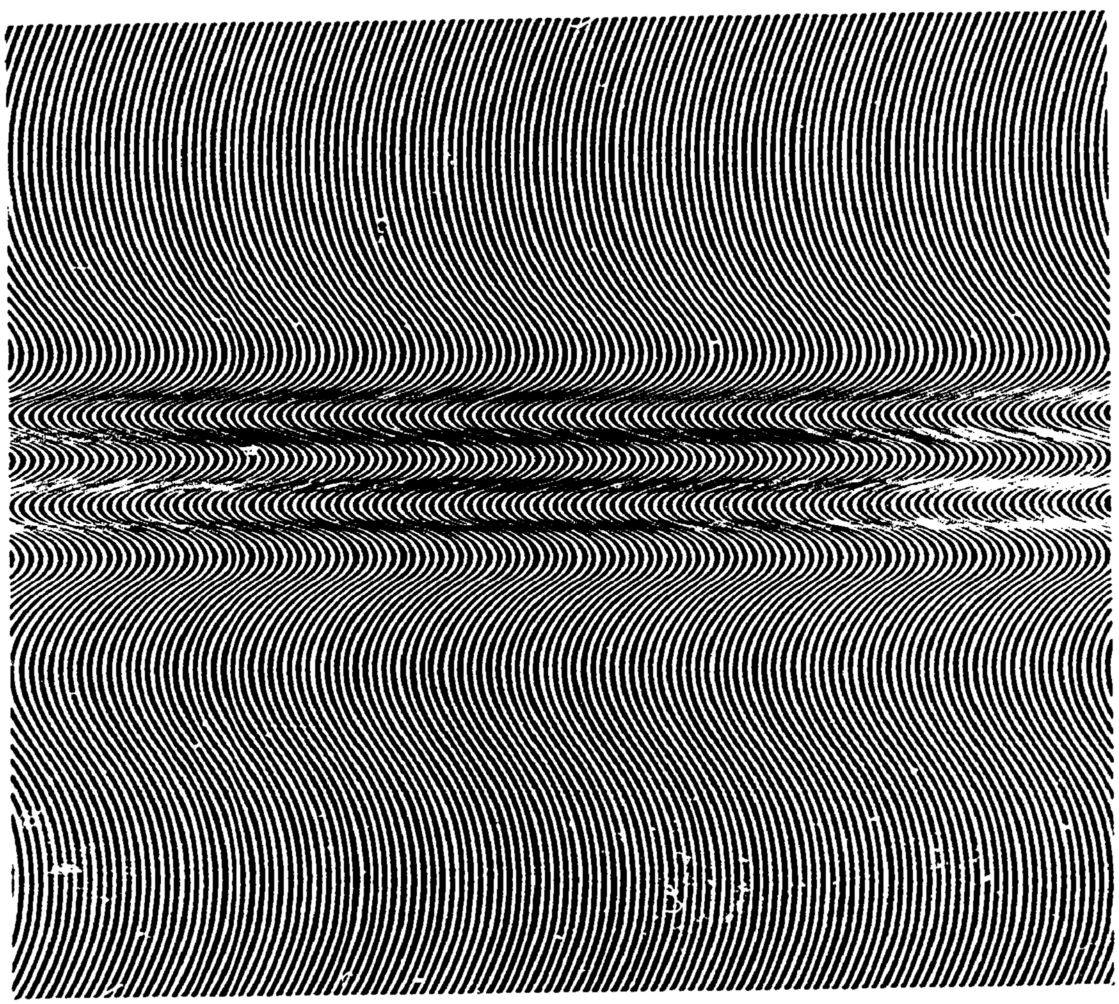
With this picture of the atom, electricity came to be seen as an integral part of the structure of matter. Faraday's ions in solution with their special properties in electrolysis were seen to be atoms of their chemical element with one or more electrons removed from or added to them.

A metal such as copper could conduct electricity by having electrons move rather freely from atom to atom. But perhaps the most striking result of this model of an atom was its application to the emission of light by atoms. Toward the end of the preceding century the brilliant work of Heinrich Hertz and Maxwell had demonstrated that light is a wave motion of electric and magnetic fields, and that these electromagnetic waves can be generated with suitable equipment so that radio and radar became possible.

It was quickly seen that the characteristic light emitted by various atoms in a flame or an electrical discharge, such as a neon tube, came from changes in the motions of the electrons in orbit in the individual atoms. In effect each atom could be regarded as a miniature radio or radar sending and receiving station. Thus the phenomenon of light became intimately involved with atoms. Atoms as electrical systems are the universal emitters and absorbers of light.



The Museum of Modern Art Collection, New York, Philip Johnson Fund



Out of the dark shadows, rose a fairy-tale vision, a weird ethereal spectacle from another world. It was like a magician's cave carved out of ice, with walls glittering and sparkling like snow crystals.

Ruz Lhuillier

The Wave Atom

At this stage of our understanding of matter, it did seem that the progress of science involved the clearing up of one mystery after another so as to reveal a very simple and unmysterious mechanical structure as the universal base of all things.

But from this point on, the further development of our scientific understanding of matter has taken a very different turn. This turn was forced on us by a number of severe difficulties encountered by the end of the first quarter of this century with the solar system model of atoms. The chemical atoms of the 19th century were hard elastic spheres that could collide with each other and rebound like billiard balls. Miniature planetary systems are neither hard nor elastic. Collisions between them should simply scatter the electrons like chaff. This is only one of several difficulties that the planetary atom encountered.

The second quarter of the century was devoted to the development of a new and very strange picture that resolved all the difficulties of the planetary atom with remarkable success. But this success has been achieved at the cost of giving up 19th century expectations that the secret of matter would be simple and easily understood in terms of ordinary human experience.

The Electron as a Wave

In the new picture the electron is no longer a particle occupying a definite place, but has become a wave centered on the nucleus and filling the whole atom. Free electrons in space are like waves on the ocean: they have a wide expanse and travel in the direction in which the electron as a particle would be moving. The positive charge in the nucleus of an atom attracts the negatively charged electron wave to it and constrains it to vibrate in a fixed pattern centered around the nucleus. These wave patterns are rather like those formed by a vibrating membrane or drumhead. There is a fundamental mode of vibration and a sequence of overtone modes as in the case of a violin string or a drumhead.

There is a strange relationship between the frequency of the wave and the energy of the particle. When two atoms or molecules collide, the wave frequency rises sharply as their electron waves begin to overlap. The corresponding increase in energy results in a powerful force pushing them apart. The effect is exactly the same as a collision of two hard

elastic spheres. Yet the electron waves are the very opposite of our normal ideas of "hardness" or "solidity". Moreover the waves are not motions of anything in our ordinary space but are rather waves of chance or probability in a shadow space called "configuration space".

These electron waves account beautifully for the identity of all atoms of the same element. The wave patterns formed by vibrating electron waves are determined solely by the electrical force exerted on the wave by the nucleus, and so produce identical patterns in all atoms with the same charge. In the simplest atom, hydrogen, the electron vibrates in the lowest frequency or fundamental mode in every hydrogen atom in the universe that is in its normal or undisturbed state. Thus hydrogen always has the same physical and chemical properties and its atoms always are identical in size and spherical shape.

If energy is added to the electron in a hydrogen atom by a collision with another atom, by electrical means, or by the absorption of light, the electron wave may be excited to vibrate in one of its higher frequency overtone modes. It then drops to a lower frequency mode by emitting a particle of light called a "photon" whose wave frequency is equal to the difference between the frequencies of the electron wave's two modes of vibration between which it was produced.

Thus the light emitted by hydrogen atoms forms a spectrum of discrete frequencies corresponding to the spectrum of overtone modes of electron wave vibration in the atom.

Spiral galaxy photographed edge on.

The Spectrum of an Element

One hundred and fifty foot spectrographic absorption tube used to study the atmospheres of planets.

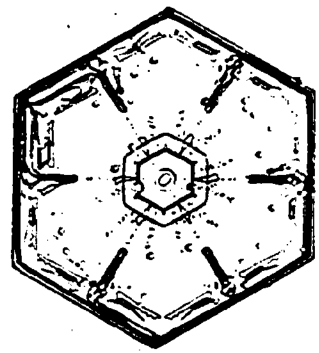
Each element has a characteristic spectrum that can be used to identify it even in the light from distant stars. If the electrons were particles moving in orbits, they should radiate light continuously with steadily increasing frequency as the electron spiraled into the nucleus. There would be no discrete spectrum and no normal or undisturbed state at which further radiation of light would stop. But when the electron wave reaches its fundamental mode of vibration there is no lower frequency overtone mode to which it can go and so no possibility of further radiation.

For example, a tuning fork can be forced to vibrate in any one of its overtone modes, but there is no way for it to produce a lower pitch than its fundamental tone. It is the same with atoms.

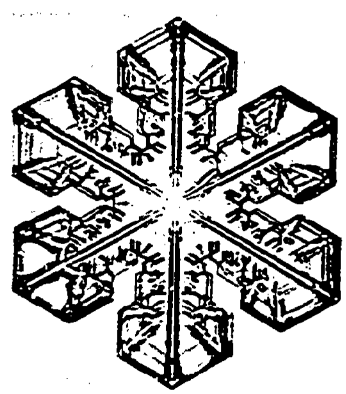
Another feature of the chemical elements for which the planetary atom could not account was their arrangement in the periodic table and the associated valence forces between atoms by which they form molecules. This the wave atom accomplishes with remarkable precision and faithfulness to all the laws of chemistry.

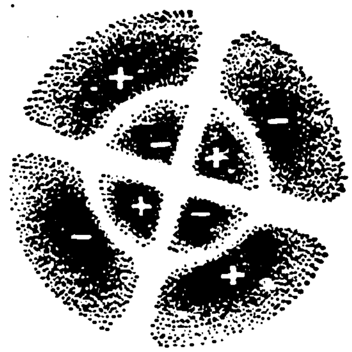
The number and characteristics of various patterns of electron waves just match the periodic arrangement of atoms. Resonances between wave vibrations in different atoms result in a decreasing frequency of wave motion as the atoms move closer together. This gives rise to attractive forces between the atoms corresponding to their decreasing energy, and these forces are of exactly the same strength and direction as those observed in molecules built of these atoms.

Indeed, the beautiful symmetries of snow crystals are a direct reflection on a macroscopic scale of the interlocking hydrogen and oxygen wave patterns responsible for forming the water molecule. With the planetary electron atom, none of this could be understood, and there was no explanation for the kinds and forms of molecules created out of atoms. The figure on the next page shows some electron wave patterns in the hydrogen atom.

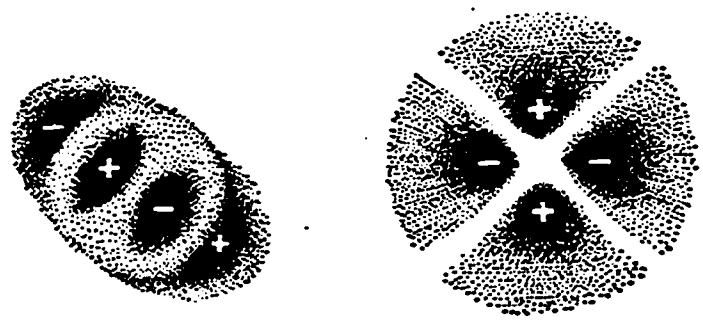


Photographs of snowflakes.

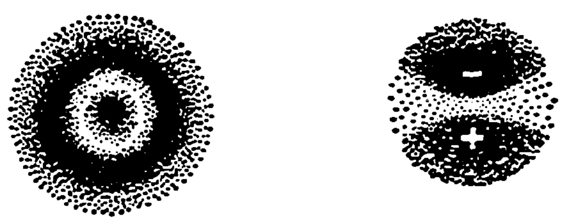




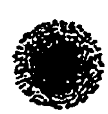
Third overtone mode



Second overtone mode



First overtone mode

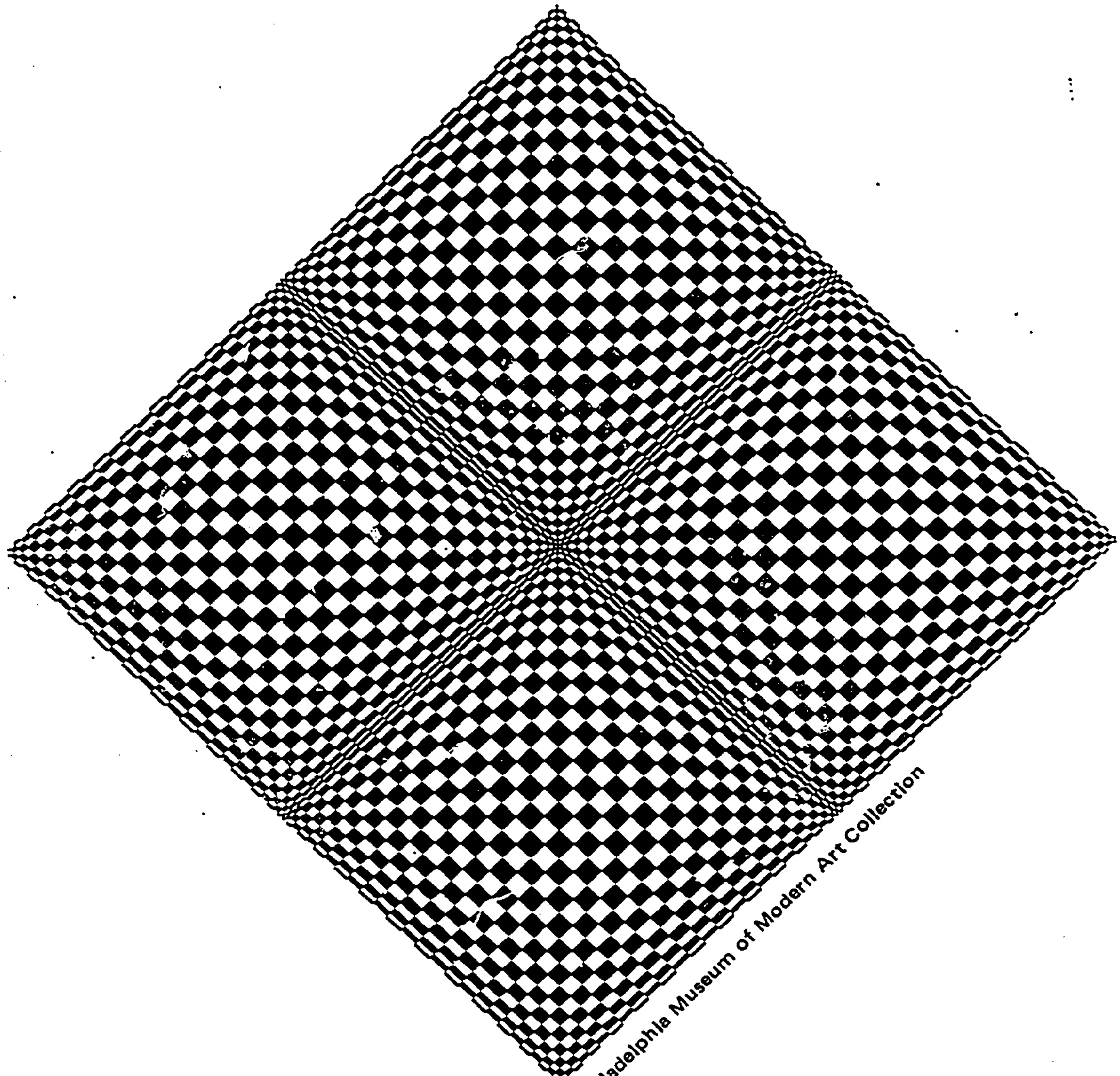


Fundamental mode

The patterns of vibration of the electron waves in a hydrogen atom are shown above for the lowest frequency fundamental mode and for several higher frequency overtone modes. The fundamental mode has the lowest energy and is the one occupied in all hydrogen atoms in their normal state. In an electrical discharge tube filled with hydrogen, the atoms are excited into various overtone modes. As they make transitions back, they emit the light spectrum characteristic of hydrogen.

These are only a few of the ways in which the wave atom has succeeded where the planetary atom simply would not work. Within the nucleus itself, where neutron and proton waves vibrating in discrete patterns with fundamental and overtone modes are involved, it has been very successful too. The extent to which this wave theory of matter, called "quantum mechanics", mirrors everything we have been able to observe about molecules, atoms, and nuclei is so broad and so precise that its reality can scarcely be questioned.

Yet in our search for the secret of matter it has forced on us a very strange picture indeed. These matter waves are sometimes called "probability waves" because their amplitude at a given point is connected with the probability of finding the *particle* at that point. They are just about as insubstantial as anything that can be imagined. Yet they give atoms their shape, size, hardness, and elasticity, and they determine the forces that atoms exert on each other in forming molecules.



Philadelphia Museum of Modern Art Collection

Looking upward and outward into the heavens has always held a special appeal for the inquiring human spirit. But much of the knowledge achieved in our century about what happens in the astronomical reaches of space has been learned by peering downward and inward into the innermost recesses of matter. Particle research has given new objectives and new impetus to cosmology, the science whose province is the universe as whole, its origins, its development and its ultimate destiny.

Victor Guillemin

Inside the Elementary Particles

At the outbreak of the second world war, it seemed that a rather complete and full understanding of matter was within reach. The triumphs of quantum mechanics were numerous and remarkable. They explained the wave atom and molecules and had made a most promising start on the structure of atomic nuclei. Just four elementary particles were required to account for the whole universe.

One could see how the nuclei of all atoms were what they were because of the laws governing the combinations of neutrons and protons out of which they were constituted. Given these nuclei, electrons would then assemble in well-defined states of vibration with predictable wave patterns to form all known atoms. These in turn could combine to form the molecules, crystalline solids, or liquids needed to account for all the manifold diversity of nature as we experience it.

Added to this was the particle of light or radiation, the photon, which accounts for the exchange of energy between atoms and molecules. We had almost in hand with these four elementary constituents of matter—neutrons, protons, electrons, and photons—a nearly complete and universal picture of the structure of matter. It was and still is a beautifully coherent and all-embracing picture of the world. We seemed close to grasping the secret of the nature of things that Lucretius had so ardently longed to unlock.

But there were a few isolated phenomena that did not fit this otherwise universal picture. At the end of the 19th century the phenomena of electricity and magnetism and the existence of electrically charged atoms or ions did not agree with the atomic theory. They seemed to be minor exceptions, but they provided the key that led to the next step in depth by revealing the nuclear atom with electrons. So at this stage what seemed to be unimportant exceptions to the general picture now appear to be leading us to another deeper level beneath or inside the neutron, proton, and electron.

Antimatter

These exceptions were the phenomena of radioactivity and the discovery of antimatter.

A radioactive nucleus transforms itself into the nucleus of an atom one step higher in the periodic table of elements by emitting an electron and another particle called a "neutrino". The neutrino is an uncharged electron, which, like the photon, is massless.

The other exception was the discovery of the antielectron or positron. This was the first instance of what we now know to be a general property of matter, namely, that for every particle of matter there is a kind of mirror image of it made of antimatter. A photon of sufficient energy can disappear and in its place an electron–positron pair can materialize. Part of the energy of the photon is used to create the masses of the particle and the antiparticle, and what is left over is shared between them as kinetic energy.

When a negatively charged electron and positively charged antielectron come together, they annihilate each other, and the energy of their masses is shared between two photons radiating away from the point at which the electrons disappeared. All the properties of an antielectron except for its mass, are the opposites of those of an electron. The antielectron did not fit the otherwise uniform scheme of things any more than did the uncharged electron or neutrino.

Strange Particles

The period since 1950 has seen a profuse elaboration of other strange particles that do not conform with the theory that prevailed in the second quarter of the century.

Leptons

They divide themselves into two classes. The first class is called "leptons", meaning lightweight or tiny particles. Two of these are uncharged electrically and are neutrinos. A neutrino has zero mass and therefore always

travels with the speed of light. At the speed of light a rotating or spinning object must spin using the direction of its motion as an axis. Both neutrinos spin counterclockwise as viewed along their direction of motion and so advance like a left-handed screw.

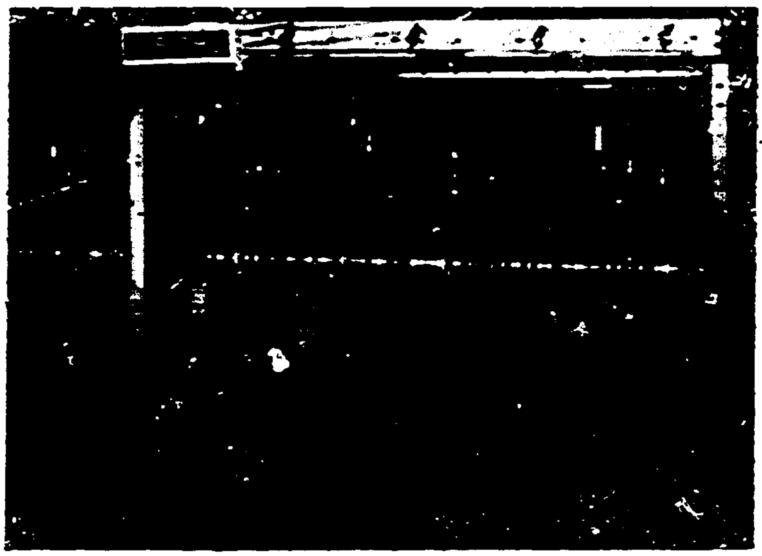
The neutrinos can be electrically charged but will take only a negative, never a positive, charge. When charged, one of them becomes an electron and the other a heavy electron or "muon". It is as though one of the neutrinos were very small and the other some 200 times larger. (The work required to concentrate the same amount of electric charge on the small neutrino would then be 200 times greater than that required to put it on the large neutrino.) Since the rest mass of a particle measures the work required to produce it, the electron would then be a charged large neutrino, and the heavy electron or muon would be a charged small neutrino with a rest mass more than 200 times that of the large neutrino.

These four particles of matter have four mirror images of antimatter in which their spin and electric charge are reversed. The two antineutrinos both spin clockwise around their direction of motion and so advance like right-handed screws. The antineutrinos can *only* be charged positively. The charged large antineutrino is the antielectron or positron, and the charged small antineutrino is the heavy antielectron or positively charged muon.

In addition to these eight, there are two other leptons, which are radiation particles (as opposed to matter particles). One is the

quantum of electromagnetic radiation or light called the photon. It has zero rest mass and a spin double that of an electron or neutrino. The other is the quantum of the gravitational field called the "graviton". It also has zero rest mass but a spin twice that of the photon.

These ten leptons form a group by themselves. We have some idea why photons and gravitons exist or at least where they fit in the



Neutrino interactions in a spark chamber.

scheme of things. But so far we have no hint as to why neutrinos and electrons exist. *The neutrino is as near nothing as anything can be and still be something. It is a point of spinning nothingness traveling at the velocity of light.* Why there are two of them and what distinguishes these two we do not know. (It was really simpleminded of me to call them "large" and "small" neutrinos. This distinction does not really stand up as a physical explanation and should not be taken seriously.) We do not know why they will only

take a negative electric charge, nor do we know why electric charge always comes in nature in the units characteristic of the electron or positron. These are "mysteries" in the detective story sense, however, which someone may some day explain.

Given the two neutrinos and the fact that they will take only one unit of negative charge, we can see, however, why there are only two electrons or charged neutrinos. Also given these four particles, we can also see the relationship to them of their four mirror images or antiparticles. At the moment we see some patterns and symmetries in nature and some hints of their interrelationship but it is very much like seeing "through a glass darkly". There are fascinating hints here of some hidden principle of order beneath the observed reality, which we ought to be able to discover if we only knew how to get at it. This is one of the really great challenges for the next generation of physicists.

Baryons

The leptons play a very important role in nature, but they are overshadowed by a much more complicated class of particles that make up most of the mass and substance of matter in the universe. These are the "baryons", meaning heavy or massive particles, and the "mesons", meaning intermediate particles. There are 18 basic baryons, which, with their 18 mirror images or antibaryons, make a group of 36. Eight of these have the same amount of spin as the neutrinos and electrons, and the other 10 have a spin three times as great. The neutron and proton belong to the

first group and all 18 baryons make up "matter" in its primary form in the universe.

Mesons

The mesons form a different class of particles comparable to the radiation particles, the photon and graviton, among the leptons. There are 17 basic mesons in all. One group of eight has zero spin and the other group of nine has one unit of spin like the photon. The mesons are related to the nuclear force that holds neutrons and protons together in the nuclei of atoms in much the same way that photons are related to the electromagnetic force and gravitons to the gravitational force.

This complicated array of what were first referred to as "strange particles" is a far cry from the neat scheme of building the whole universe out of just four elementary constituents—neutrons, protons, electrons, and photons—which largely characterized the first half of this century. Just as the first quarter of the century was largely devoted to the planetary atom and the second quarter to the wave atom, so it seems that this third quarter is largely concerned with the quest for understanding this subatomic strata of strange particles on which the wave atom that makes up our familiar world rests.

Quarks

Quite recently a fascinating breakthrough has been made that brings a great deal of order into this bewildering assortment of strange particles. It has been found that all 18 particles of matter called baryons, including

the familiar neutron and proton, can be explained by supposing that each one is a complex system of three elementary particles called "quarks".* The corresponding 18 antiparticles are then made up of three antiquarks. The 17 mesons are each a system consisting of a quark and antiquark in intimate association.

The quarks themselves are very strange objects indeed. Two of them make a pair of "common" quarks with a positive electric charge two-thirds that of an electron and a negative electric charge one-third that of an electron. The third or "strange" quark has one unit of a property called "strangeness" and a negative electric charge one-third that of an electron. The neutron and proton and four other baryons, called "delta" particles, are made up of only the first two or common kinds of quarks and so have zero strangeness. The remaining particles have one or more of the third kind of quark in them and so one or more (up to three) units of strangeness. The most common meson, a triplet of three particles called "pions", and a single particle called the "eta", are quark—antiquark combinations involving only the common quarks. Others contain either a strange quark or a strange antiquark.

A few examples will show how all these particles can be constructed of quarks. Denote the two common quarks by P with an

*Murray Gell-Mann, an American physicist, formulated the quark theory. He took the name from "Three quarks for Muster Mark", a line that H. C. Earwicker, a bartender, repeats in James Joyce's *Finnegan's Wake*.

electric charge of $+\frac{2}{3}$ and R with an electric charge of $-\frac{1}{3}$, and the strange quark by S with a charge of $-\frac{1}{3}$ and one unit of strangeness. There are only four ways of combining the two common quarks into three-quark particles. These are PPP, PPR, PRR, and RRR. These constitute the four delta particles with electric charges +2, +1, 0, and −1 respectively. There are three combinations with one S quark, two combinations with two S quarks and, of course, only one with three S quarks. This last, SSS, is called the Omega Minus, but it had not been discovered at the time the quark theory was developed. It was predicted with all its physical properties including its three units of strangeness and then was discovered sometime later. This discovery was a great triumph for the quark theory. All ten of these particles have spins three times that of the neutron and proton.

The neutron and proton belong to another group of eight baryons with small spin. The neutron consists of two R quarks and one P quark and so has zero electric charge since the R's have $-\frac{1}{3}$ each and the P has $+\frac{2}{3}$ charge. The proton is two P quarks and one R quark and so has an electric charge of +1 unit. Four others in this group have one S quark and the remaining two have two S quarks each and so two units of strangeness.

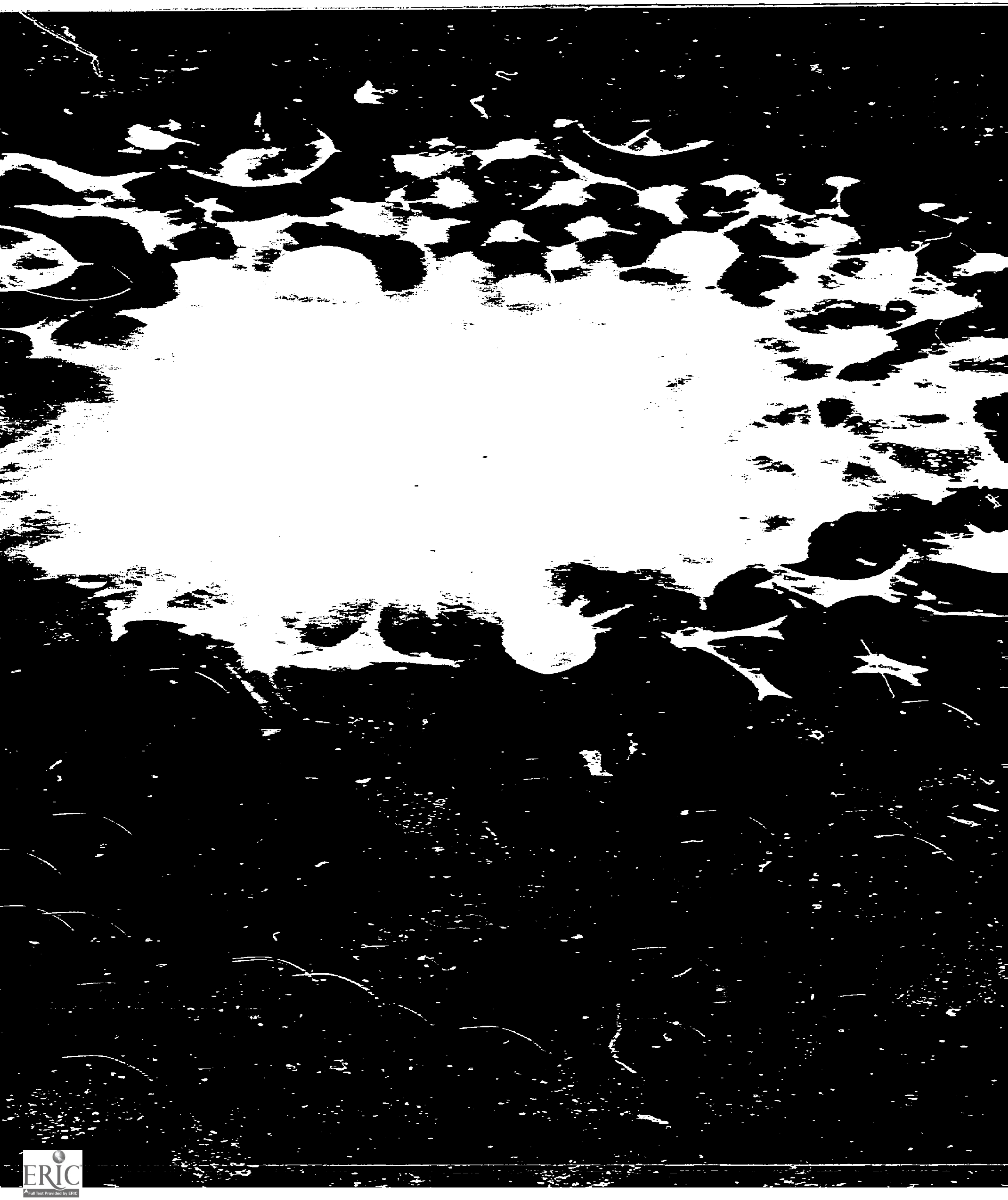
The quark model is remarkably successful in accounting for the whole complicated array of baryons and mesons with all their properties of spin, electric charge, strangeness, and mass. This success rather persuasively establishes the reality of quarks as the inner

structural element of all these particles. Yet so far every effort to observe them has been unsuccessful. It may be that they are so massive that none of our present high-energy particle accelerators provides sufficient energy to dislodge one from a neutron or proton. A major motive for building an immense 200 billion electron volt (Bev) accelerator* is to determine whether this will be sufficient to produce individual quarks.

On the other hand, it may well prove to be the case that quarks can only occur in combinations of three or in pairs of quarks and antiquarks. If this were really a law of nature, then quarks could never be observed singly or in pairs, but only in the combinations already observed. In that case they would remain an interesting and successful mathematical device for explaining what we do observe, but their reality and existence would remain questionable. My own opinion is that this latter alternative is the probable one, and that individual quarks will never be observed. This, however, is only an opinion or hunch, and other physicists deeply involved in this question do not share it.

*This is now being built at the National Accelerator Laboratory near Batavia, Illinois.

The 2-mile electron accelerator at Stanford University.



The same thrill, the same awe and mystery, come again and again when we look at any problem deeply enough. With more knowledge comes deeper, more wonderful mystery, luring one on to penetrate deeper still. Never concerned that the answer may prove disappointing, but with pleasure and confidence we turn over each new stone to find unimagined strangeness leading on to more wonderful questions and mysteries—certainly a grand adventure!

Richard Feynman

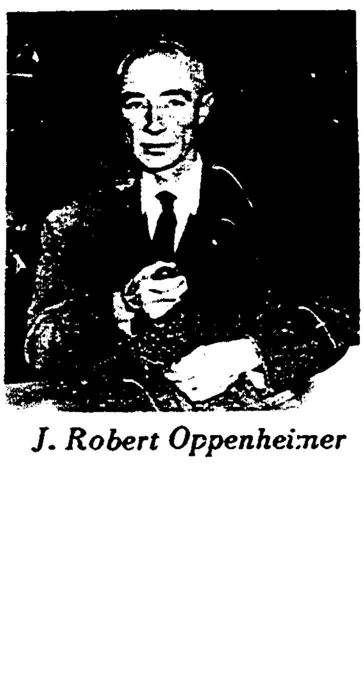
The Mystery of Matter

We have come a long way since the early Greeks in our search for the secret of matter, and there have been many surprises along the way. Let us pause and reflect on what we have learned from the quest so far.

One thing we have learned is an appreciation for the depth, openness, and strangeness of nature. For the 19th century and the first part of the 20th, nature seemed shallow and more or less transparent. The secrets of nature seemed to lie just below the surface of things. The word "mystery" was never used in scientific writing, because it was widely believed that science was rapidly dispelling all

mysteries. Everything seemed to be fitting into an intelligible and rather simple pattern. Soon one could anticipate a single great formula that would explain everything.

The actual course, as we have seen, has proved quite different. Nature has shown unexpected and amazing depths. The quest for the secret of matter has led us down into one depth after another. At each plunge the world that has been revealed to us has possessed strange new wonders and symmetries. At each stage it has proved amazingly intelligible to the human mind, but nevertheless in terms increasingly far removed from the obvious or familiar world of our everyday experience.

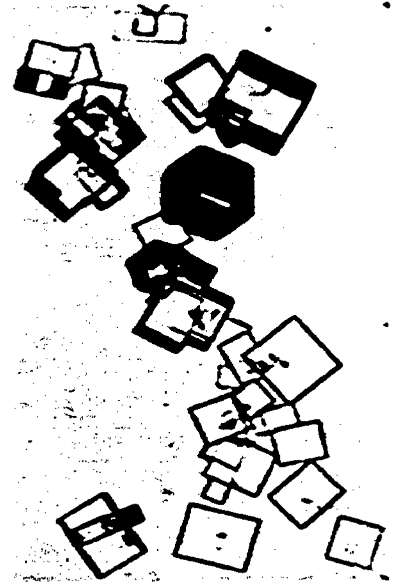

J. Robert Oppenheimer

J.Robert Oppenheimer has likened all of science to a vast underground palace with an unending series of interconnecting rooms.* At first as we began to explore the antechambers near the entrance, it seemed a familiar building of limited size much like other buildings we were familiar with. But as this century has advanced unsuspected rooms have been entered and surprising interconnecting passageways discovered. *Each new room or suite of rooms has been full of surprises, strange new beauties, and unsuspected wonders.* Yet each time we began to think that we had reached the palace boundary and were in the innermost rooms, hidden doorways have been stumbled upon, which have led us into still deeper and more amazing sections of the palace.

**Science and the Common Understanding*, Simon and Schuster, Inc., New York, 1954, pp. 83-85.

Others have likened science to a crystal growing in solution and revealing new symmetries and beauties as the fingers and facets of the crystal multiply. The crystal has a unity of its own, but it is unbounded in its possibilities for new growth. As science has developed, each mystery that has been cleared up, each question that has been answered has only posed several new questions.

This quality of reality in which each question opens up several more questions in a divergent rather than convergent series represents genuine unfathomable mystery. It is not a question of individual mysteries that can be solved one at a time. Instead it is an overall state of affairs characteristic of the whole quest for understanding reality itself. This situation alone has introduced a sense of mystery and wonder into modern science, which is quite the opposite of the spirit of science in the 19th century.



Polyhedral salt crystals growing from solution.

There are many ways in which the quest for the inner secret of matter has developed this sense of mystery. For the 19th century, matter possessed the one simple property of mass. By now we recognize several independent properties in complex admixtures in different samples of matter. It is by virtue of mass that the gravitational attraction of objects takes place. Electric charge determines the electromagnetic forces on matter and is wholly independent of mass. A third property, possessed by neutrons and protons but not by electrons (ordinary or heavy), might be called "nuclearity" and determines the very strong force that holds neutrons and protons together in nuclei. Another property

determines the ability of matter to emit or absorb uncharged electrons or neutrinos.

If quarks exist, they possess a fifth property independent of these others by virtue of which they exert immensely powerful attractive forces on each other. The three common constituents of matter possess these properties in varying combinations. The electron has mass and electric charge but no nuclearity; the neutron has mass and nuclearity but no electric charge; while the proton has all three.

Even more amazing than this variety in the basic composition of matter is the existence for every form of matter of its mirror image in antimatter. Because of this, matter and antimatter can be materialized in equal quantities and then later be annihilated. This lends an impression of insubstantiality and transitoriness to matter, which is quite at variance with earlier convictions about it. This character of matter is further emphasized by the universal applicability of quantum mechanics whereby all particles of matter dissolve and smear out into probability waves in configuration space.

The old materialism that reduced everything to simple masses in motion has certainly been swept away. The contemporary materialist must visualize material reality in terms of matter and antimatter waves in a kind of shadow world, and consider them to be made up of mass, charge, nuclearity, and other basic constituents according to various recipes. It is a strange and shadowy kind of materialism with none of the simple, substantial, and sturdy obviousness of the old established kind.

In preparation for Congressional hearings before the Joint Committee on Atomic Energy on the national program in high-energy physics, a collection of papers by leading high-energy physicists was prepared for the purpose of asking for the appropriation of large funds for constructing the 200-Bev accelerator. Something of the new spirit of science with its aura of mystery about the quest for the secret of matter is conveyed in the concluding paragraph of the paper by Steven Weinberg in this collection:*

> Instead of feuding with one another for public favor, it would be fitting for scientists to think of themselves as members of an expedition sent to explore an unfamiliar but civilized commonwealth whose laws and customs are dimly understood. However exciting and profitable it may be to establish themselves in the rich coastal cities of biochemistry and solid state physics, it would be tragic to cut off support to the parties already working their way up river, past the portages of particle physics and cosmology, toward the mysterious inland capital where the laws are made.

Earlier generations of scientists would never have spoken of what they considered they were up to in such terms or with such an image. Yet passages such as this appear with increasing frequency in contemporary scientific literature. The whole atmosphere today is in sharp contrast to that of the last century. Yet the notions about science that characterize the attitudes of the general public today are still largely derived from the convictions

*_Nature and Matter: Purposes of High Energy Physics_, L. C. L. Yuan, (Ed.), Brookhaven National Laboratory, Upton, Long Island, N. Y.

about it that scientists held early in this century.

It is interesting to speculate on where the quest for the secret of matter may ultimately lead. If quarks exist and individual ones are in time observed, a persistent question about them will remain. Are they the ultimate elementary particles of nature, or is there a still deeper level that describes what quarks are made of? On the other hand, if quarks have no individual existence, perhaps the basic reality of matter is to be found in the mathematical operation that defines them. This operation is a rotation in a special kind of space called "Hilbert Space", which is known as a special unitary transformation in three dimensions and designated as SU(3).

Indeed, there is an alternative to quarks called the "bootstrap" model in which all of the many baryons and mesons are simply combinations of each other. In this model there are no elementary constituents of matter but instead a democracy of particles each of which is a combination of two or more other particles. Matter then materializes through a mathematical operation that produces it out of nothing in much the same way as a man lifting himself by pulling on his bootstraps. At the moment we do not know which of these possibilities, if either, will prove to be the case.

This situation suggests a parallel to a famous passage in the Chandogya Upanishad in which a father instructs his son about the nature of reality through various actions like peeling an onion, or dissolving a grain of salt in water. As layer after layer is removed, the

boy finally reaches a point at which he finds nothing at all. There is a void at the heart of the onion, and the salt grain disappears as the last layer dissolves. Yet the father explains that the invisible central point is the ultimate essence, not only of the phenomenal universe, but of the boy himself: "That which is the subtil essense, in it all that exists has its self. It is the True. It is the Self, and thou, O Svetaketu, art it."*

The 19th century belief that the maze through which it was threading toward the one great formula—the essence of all material existence at its center—is being replaced by another possibility that suggests itself more and more insistently: *In the innermost chamber we will find simply nothing. The end of the quest for the secret of*

**A Short Comparative History of Religions*, T. H. Robinson, Gerald Duckworth, London, 1951, p. 80.

matter may be no "thing" existing in space and time at all, but rather a hypothetical quark that doesn't exist or a three-dimensional mathematical bootstrap operation in Hilbert Space.

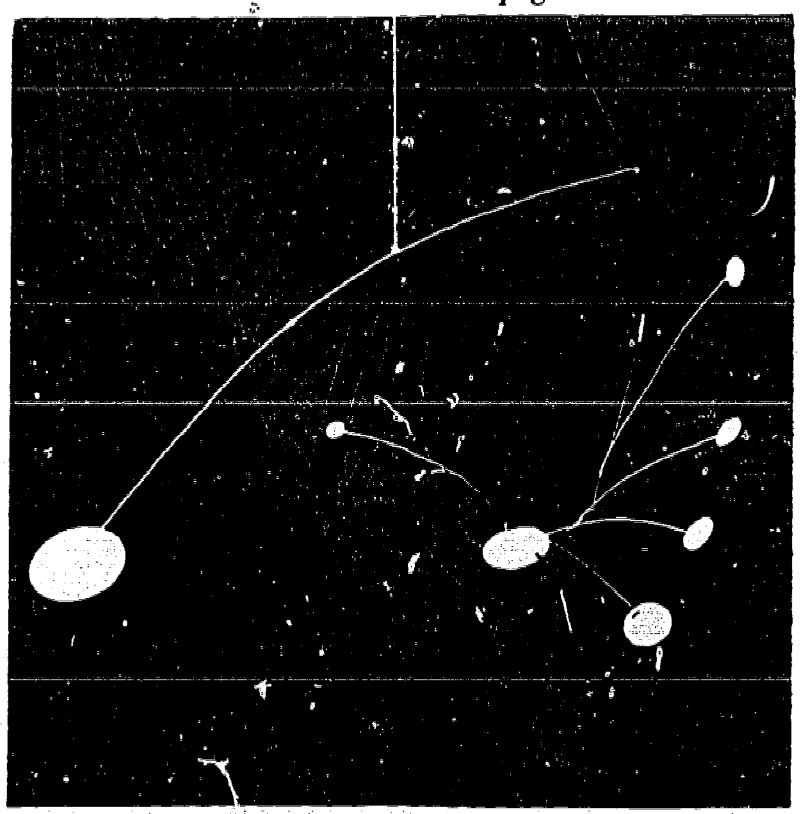
Like Plato's famous cave, it may turn out that the whole material universe in three-dimensional space and time with all its seeming substantiality is at heart made up of mere shadows of realities that transcend space and time and so are inaccessible to our direct observation. The mysterious probability waves in configuration space that describe all the components of atoms so completely are suggestive of just such an outcome. So too is the complementary relationship between matter and antimatter. In any event, however, the aura of mystery that surrounds the whole question of the secret of matter seems now to be a permanent characteristic that no conceivable future research is likely to dispel.

It should be evident from all this that when we speak of "mystery" in science we no longer mean unknown areas or puzzles which research in the future may be expected to clear up. We are not speaking of a mystery of anything unknown at all. Rather we are speaking of the mysteriously amazing character of the known. There is a true mystery of the known and our modern knowledge in science confronts us with that mystery very strongly. A very important element of this mystery of the known is the way in which our knowledge of matter keeps beckoning us toward transcendent realities beyond space and time. The more deeply we probe into the

secret of matter the more our knowledge seems to point us beyond space–time.

The hints grow stronger that the underlying reality of things in nature is to be found beyond nature in a kind of super-nature or hyper-nature in which all space and time is immersed. But in all human experience the essence of mystery has resided in the sense of an invisible and unseen reality enveloping the visible and seen world of direct experience. Throughout the whole of man's life on earth except for just the last two centuries of his history this has been an essential element of all human experience of external reality. It is toward a return to this primordial mystery that the modern quest for the secret of matter seems surely to be leading us.

Mobile that is shown in motion on page 18.



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Quotations

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Page	
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4	Metropolitan Museum of Art, New York, Rogers Fund, 1911.
7	Top, U. S. Department of Agriculture; bottom, Cyril Stanley Smith.
9	Hale Observatories
10	From *PSSC Physics*, D. C. Heath and Company, 1965.
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18	"Hanging Mobile", Alexander Calder, 1936. The Museum of Modern Art, New York, Mary Callery Collection.
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21 Top, Library of Congress; bottom, Sir George P. Thomson.

25 Hale Observatories

26 "Current", Bridget Riley, 1964. The Museum of Modern Art Collection, New York, Philip Johnson Fund.

30 Top, Hale Observatories; bottom, National Center for Atmospheric Research.

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34 "Color Motion", Edna Andrade, 1965. Philadelphia Museum of Modern Art Collection, Photograph by A. J. Wyatt.

39 Nevis Laboratories, Columbia University and Brookhaven National Laboratory.

45 Stanford University

46 William Thonson

48 Alan W. Richards

49 George Braziller, Inc., New York

53 Twelfth century Chinese painting after a 4th to 5th century design attributed to Ku K'ai-chih of the Chin dynasty. The Smithsonian Institution, Freer Gallery of Art, Washington, D. C.

55 "Hanging Mobile", Alexander Calder, 1936. The Museum of Modern Art, New York, Mary Callery Collection.

The Author

William G. Pollard, an articulate and well-known lecturer and author, is an Episcopal priest and a physicist. He has been executive director of Oak Ridge Associated Universities (ORAU) since 1947. ORAU sponsors nuclear-related research and conducts a variety of programs for the education and training of professional people and the general public in nuclear fields. Dr. Pollard received his B.A. from the University of Tennessee, his M.A. and Ph.D. from Rice Institute, and his D.D. from Hobart College. He is the author of numerous articles and books including *Chance and Providence*, Charles Scribner's Sons, 1958; *Atomic Energy and Southern Science*, ORAU, 1966; *Man on a Spaceship*, Claremont Graduate School and University Center, 1967. *The Mystery of Matter* is adapted from a chapter in his most recent book *Science and Faith: Twin Mysteries*, Thomas Nelson and Sons, 1970.

The Cover

Photograph of a snowflake.

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